

Design and Experimental Study of a Low-Temperature Micro-Displacement Actuator (Postprint)

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Abstract

For applications in polar astronomical telescopes, a low-temperature micro-displacement actuator has been developed, and performance testing experiments were conducted under both room-temperature and low-temperature conditions to obtain its performance specifications. Three common structural configurations of large-travel high-precision micro-displacement actuators were analyzed, and the displacement scaling type was selected as the basic structure. The actuator employs a low-temperature stepper motor as the driving element and utilizes a screw transmission with a special backlash-eliminating structure as the displacement scaling mechanism, thereby achieving a design featuring high stiffness, low-temperature resistance, compact structure, and good sealing performance. Experimental results demonstrate that the designed low-temperature micro-displacement actuator can achieve a stepping accuracy of $1 \pm 0.082 \text{ m}$ under room-temperature conditions while meeting the design requirements for load capacity; under low-temperature conditions, the stepping accuracy can reach $2 \pm 0.404 \text{ m}$. The developed micro-displacement actuator will provide important technical support for the construction of segmented polar astronomical telescopes.

Full Text

Design and Experiment of a Cryogenic Micro-Displacement Actuator

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Abstract

Taking the polar astronomical telescope as the application background, this paper develops a cryogenic micro-displacement actuator and conducts performance testing experiments at both room temperature and low temperature to obtain its performance parameters. Three common structural forms of long-travel, high-precision micro-displacement actuators are analyzed, and the displacement scaling type is selected as the basic structure for the cryogenic micro-displacement actuator. The actuator employs a cryogenic stepper motor as the driving element and utilizes a screw drive mechanism with a special anti-backlash structure as the displacement scaling mechanism, achieving a design that features high stiffness, cryogenic resistance, compact structure, and good sealing performance. Performance testing experiments demonstrate that the designed cryogenic micro-displacement actuator achieves a step accuracy of $1 \text{ m} \pm 0.082 \text{ m}$ at room temperature while meeting the design requirements for load capacity. At low temperature, the step accuracy can reach $2 \text{ m} \pm 0.404 \text{ m}$. The developed actuator will provide important technical support for the construction of segmented polar astronomical telescopes.

Keywords: micro-displacement actuator; astronomical telescope; accuracy; cryogenic; screw drive

Introduction

The advancement of astronomy has imposed increasingly stringent requirements on astronomical telescopes. For radio telescopes, increasing the aperture is the most important approach to improving resolution and sensitivity. However, the reflector surfaces of large antennas are limited by manufacturing technology and cannot be realized using a single panel. Active surface technology provides crucial technical support for manufacturing extremely large reflectors by using smaller sub-panels to form a primary reflector with a certain surface accuracy. To adjust the shape of the primary reflector, each sub-panel requires support and adjustment by micro-displacement actuators [1]. As the core component of active surface technology, the micro-displacement actuator is a precision linear displacement output device that supports and adjusts the sub-panels. Given that the primary reflector surface must meet the imaging requirements of radio telescopes, micro-displacement actuators must provide high displacement output accuracy, large load capacity, high stiffness, and millimeter-level effective stroke. Radio telescopes employing active surface technology that have been built worldwide primarily use self-developed micro-displacement actuators [2-4].

The telescope site is one of the factors affecting observation performance. An excellent telescope site requires clean atmosphere, low wind speed, high atmospheric transmittance, and low water vapor content [5]. The high-altitude regions of Antarctica meet these conditions, and Dome A, which China reached first, is recognized as the best optical/infrared astronomical observation site on

Earth and is highly suitable for submillimeter-wave and terahertz astronomical observations [6]. China has already installed small astronomical telescopes in the Dome A region of Antarctica and plans to construct large-scale terahertz astronomical telescopes in the future [7]. For micro-displacement actuators used in Antarctic astronomical telescopes, additional characteristics such as cryogenic resistance and protection against wind and snow erosion are required. Addressing the performance requirements of active surface technology for micro-displacement actuators and the environmental conditions of Antarctica, this paper designs a cryogenic micro-displacement actuator and conducts performance testing experiments to obtain its performance parameters.

Design of Cryogenic Micro-Displacement Actuator

Structural Form of Cryogenic Micro-Displacement Actuator

Common structural forms of long-travel, high-precision micro-displacement actuators mainly include three types. The inchworm-type micro-displacement actuator is based on the motion form of an inchworm and driven by piezoelectric ceramics or shape memory alloy elements. This type of actuator can theoretically achieve unlimited effective stroke [8], and these driving elements offer high precision. However, inchworm-type micro-displacement actuators have complex control systems. The displacement scaling-type micro-displacement actuator adds a displacement scaling mechanism behind the driving element. The scaling mechanism primarily includes reducers, hydraulic reduction mechanisms, precision lead screws, and flexible hinges [9]. The micro-macro 叠加式 (micro-macro 叠加式) micro-displacement actuator consists of a macro-motion part for large-travel, micron-level positioning and a micro-motion part for small-range, nanometer-level positioning [10]. The disadvantage of this type is that both the mechanical structure and control system are complex, and mature commercial products are rare.

Through analysis and comparison of these three structural forms, the displacement scaling-type micro-displacement actuator offers a relatively simple structure and convenient design. By combining the driving element with the displacement scaling mechanism, it can output high-precision displacement over a large travel range. Therefore, the cryogenic micro-displacement actuator designed in this paper adopts the displacement scaling structural form. Table 1 shows the structural scheme of the cryogenic micro-displacement actuator.

Structural scheme of cryogenic micro-displacement actuator

Design Details

The design of the displacement scaling-type micro-displacement actuator includes the selection of the driving element, displacement scaling mechanism, and overall support frame structure. The cryogenic micro-displacement actuator employs a precision cryogenic stepper motor as the driving element. Stepper

motors have no cumulative error and can output small step angles through electrical subdivision control. The scaling mechanism uses a precision trapezoidal sliding lead screw. This design ensures that the lead screw will not seize at low temperatures and can effectively reduce the backlash of the screw drive. The small-lead thread structure is compact, occupies minimal space, and provides self-locking capability.

The transmission nut adopts a special anti-backlash structure to eliminate thread fit clearance. Guide keys serve as the guiding mechanism, and their machining accuracy must be ensured for precision machinery applications. Both end caps are equipped with left and right rotation prevention structures, providing certain sealing performance to prevent wind and snow erosion of internal components. The actuator housing is made of materials with a face-centered cubic lattice structure—chromium-nickel stainless steel—which exhibits temperature-independent impact toughness, good corrosion resistance, cryogenic strength, and mechanical properties, along with excellent machinability. Except for the stepper motor and bearings which are purchased components, all other parts are made of chromium-nickel stainless steel to ensure consistent thermal deformation of components at low temperatures. For lubrication, low-temperature extreme pressure grease is selected to ensure normal operation in cryogenic environments.

The control system for the cryogenic micro-displacement actuator consists of a computer, a Panasonic programmable logic controller (PLC), a stepper motor driver, and a 24 V stabilized DC power supply. The control program is developed using the universal ladder diagram programming tool for PLCs and VC++ 6.0, meeting the open-loop performance testing requirements of the actuator. The overall envelope dimension of the actuator is 75×120 mm, with a compact structure and smoothly transitioned housing surface that can effectively avoid snow accumulation. The appearance of the cryogenic micro-displacement actuator is shown in Figure 1.

[Figure 1: see original paper] Appearance of cryogenic micro-displacement actuator

Performance Testing of Cryogenic Micro-Displacement Actuator

During performance testing experiments, the cryogenic micro-displacement actuator is mounted on a measurement platform, and a Heidenhain length gauge is used to detect the output displacement and record data. The measurement system is placed inside a CT2502 low-temperature test chamber. To mitigate the adverse effects of compressor vibration during chamber operation on the tests, a loading device is also designed. After the temperature is lowered to the set point, the system is held for temperature stabilization before testing begins. Performance under both no-load and loaded conditions is evaluated. Figure 2 shows the actuator performance testing at room temperature (left) and low

temperature (right).

[Figure 2: see original paper] Test at ambient temperature and test at low temperature

Room Temperature Performance Testing

Step Accuracy Testing at Room Temperature

Initially, the step accuracy under no-load conditions is tested. The length gauge position remains fixed while the motor drives the actuator output end. Step sizes of 1 m, 2 m, and 5 m are used, and length gauge readings are recorded. The theoretical output displacement is compared with the actual output displacement, and the standard deviation and mean values are calculated. Table 2 presents the mean and standard deviation for the three step sizes.

Mean and standard deviation of test for three step sizes (step size: 1 m, 2 m and 5 m)

The test results indicate that at room temperature, the actuator's no-load step accuracy can reach $1 \text{ m} \pm 0.082 \text{ m}$. According to the design requirements, the maximum axial pressure load must reach 60 N. Considering a load margin, the maximum axial pressure load is increased to approximately 68 N. The step accuracy under a 68 N axial pressure load is then tested. The test results show that under load influence, the actuator's step accuracy decreases slightly to $1 \text{ m} \pm 0.114 \text{ m}$, but the impact is minimal.

Repeat Positioning Accuracy Testing at Room Temperature

The repeat positioning accuracy test method is illustrated in Figure 7. The actuator's output end moves to a certain position (point A), the length gauge display is zeroed, then moves 10 m to point F, and finally returns from point F to point A in the opposite direction. The length gauge data is recorded, and statistical analysis is performed. The test data is shown in Table 3.

Test data of repeatability positioning (unit: micrometer)

The data reveals that when reversing direction at point A toward point B, a portion of the theoretical output displacement is offset by backlash. However, this does not affect the repeat positioning accuracy. The standard deviation at each position is calculated from the five sets of experimental data, with the maximum standard deviation being 0.052 m (Table 4). Therefore, the actuator's repeat positioning accuracy at room temperature is $\pm 0.052 \text{ m}$.

Standard deviation of 5 groups of experimental data (unit: m)

[Figure 7: see original paper] Test method for repeatability positioning accuracy

Low Temperature Performance Testing

For cryogenic micro-displacement actuators, performance in low-temperature environments is equally important. According to design requirements, the actuator must operate in environments as low as -40°C . Therefore, step accuracy at -40°C must be tested. When the low-temperature chamber reaches -40°C and is held for one hour, the actuator surface becomes severely frosted and partially iced, yet the actuator continues to operate normally without jamming, abnormal noise, or other undesirable phenomena.

Using the same method as room temperature performance testing, the cryogenic micro-displacement actuator's step accuracy at -40°C is measured. The test results demonstrate that the actuator can achieve a step accuracy of $2\ \mu\text{m} \pm 0.404\ \mu\text{m}$ in this environment. Compared with room temperature step accuracy, the low-temperature accuracy degrades. This deterioration occurs because the actuator is placed inside the low-temperature chamber while the testing end must remain outside due to temperature limitations, and the stiffness of connecting components between the driving end and testing end significantly affects the step testing accuracy. Additionally, micro-vibrations present inside the low-temperature chamber during testing cause some interference with the results. Future improvements to the low-temperature testing method will further enhance the low-temperature step testing accuracy of the micro-displacement actuator. The frosting and freezing phenomena during low-temperature testing are shown in Figure 9.

[Figure 8: see original paper] Test results of step accuracy at -40°C

[Figure 9: see original paper] Frosting and freezing in test at low temperature

Conclusion

This paper designs a cryogenic micro-displacement actuator for active surface technology and conducts a series of performance tests. The designed cryogenic micro-displacement actuator achieves a step accuracy of $1\ \mu\text{m} \pm 0.082\ \mu\text{m}$ at room temperature and meets the load capacity design requirements. Under an axial load of 68 N, the actuator can achieve a step accuracy of $1\ \mu\text{m} \pm 0.114\ \mu\text{m}$. The repeat positioning accuracy of the cryogenic micro-displacement actuator is $\pm 0.052\ \mu\text{m}$. Low-temperature test results indicate that at -40°C , the actuator can achieve a step accuracy of $2\ \mu\text{m} \pm 0.404\ \mu\text{m}$. Comprehensive test results demonstrate that the cryogenic micro-displacement actuator satisfies the relevant technical design requirements. The research on this actuator provides fundamental technical conditions for the future construction of polar astronomical telescopes.

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English Abstract

Taking the polar astronomical telescope as application background, a cryogenic micro-displacement actuator is designed and then tested at room temperature and low temperature environment respectively. Performance parameters of this actuator is acquired. Three kinds of structural forms of long travel high-accuracy micro-displacement actuator are analyzed; the displacement scaling is chosen as the basic structure of this cryogenic micro-displacement actuator. Cryogenic step motor is employed as the drive element, and the screw drive mechanism which contains specific anti-backlash structure is selected as the displacement scaling mechanism. This design develops a micro-displacement actuator which maintains satisfactory qualities such as high stiffness, low temperature resistance, compact structure and good leakproofness. Performance tests are also carried out. Test results indicate that the cryogenic micro-displacement actuator can achieve the step accuracy of $1 \text{ m} \pm 0.082 \text{ m}$ at ambient temperature, and its load capacity meets the design requirements; meanwhile, the cryogenic micro-displacement actuator can achieve the step accuracy of $2 \text{ m} \pm 0.404 \text{ m}$ at low temperature. This cryogenic micro-displacement actuator will provide important technical support for the construction of the splicing polar astronomical telescope.

Keywords: Micro-displacement actuator; Astronomical telescope; Accuracy; Cryogenic; Screw drive

Note: Figure translations are in progress. See original paper for figures.

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